Industrial Scraps Valorization: Designing Products to Make Detached Value Chains Circular

Cappelletti Federica(✉), Rossi Marta, Ciccarelli Marianna, and Germani Michele

Università Politecnica delle Marche, Via Brecce Bianche 12, 60131 Ancona, Italy
f.cappelletti@pm.univpm.it

Abstract. Intersecting value chains for the sake of sustainability is a very challenging target; however, eco-design can enable it. The high performing products required by the customers have boost the research, development and employment of composite materials, that often cannot be handled at their End of Life. The literature lacks hints and methodologies that support this. The paper presents a methodology whose core is the redesign of components, so that their material can be substituted with scraps deriving from other products. It aims to a symbiosis between enterprises that are active on different sectors; it is applicable to composites, as shown in the case study and offers an alternative to the cannibalization and low demand for remanufactured products because, unlike previous works, it investigates how materials can be employed in different products. The case study quantitatively evaluates the environmental benefits derived from the symbiosis of two companies, active in different sectors. Process scraps and product are analyzed; a re-design follows; the scraps are remanufactured and used as new material. The results highlight the need for a strong cooperation between companies, to take advantage of value hidden in their products. Future studies should focus on the economic impacts, considering not only the technical sphere, but also including the benefits echoing on company's images.

Keywords: Circular economy · Design for de-manufacturing · Composite materials · Design for disassembly · Industrial symbiosis

1 Introduction

Circular Economy (CE) is strictly bounded to the concept of industrial symbiosis (IS) to use resources in a more sustainable way than a traditional and linear economy. An IS is a form of brokering to bring companies together in innovative collaborations in which waste or by-products of an industry or industrial process become the raw materials for another.

IS requires an enterprise not only to harmoniously encompass all its internal departments but also to cooperate with downstream and upstream actors of the supply chain. The field of research in IS is immature and more research is necessary to demonstrate the

S. Gerbino et al. (Eds.): JCM 2022, LNME, pp. 39–50, 2023.
https://doi.org/10.1007/978-3-031-15928-2_4

economic, environmental, and social benefits and to get practical design insights related to IS [1]. CE and IS have the End of Life (EoL) product phase as starting point: it must generate suggestions and feedback to be implemented at the design phase [2]. EoL is a very delicate lifecycle phase; it must be planned to make it efficient; when it comes to EoL strategies such as reuse, remanufacture and recycle, each product and material need special consideration, especially when composite materials, which are the focus of this paper, are employed.

The use of composite materials is growing with the global business sector for composite products has reached about £73 billion by 2020 [3]. Consequently, enterprises must face the big challenge of developing approaches and technologies to optimize the waste generated from their manufacturing operations and EoL [4]. Three are the main options currently implemented for treating composite wastes: landfill, incineration and recycling. Oliveux et al. [5] calculated the related environmental impact of these strategies obtaining significant negative burdens on the environment for landfilling and incineration treatments, while minor values for the recycling process. Landfill of composite waste is banned in Germany (since 2009) and other EU companies are expected to follow this route; furthermore, when they are incinerated, around 50% of the composite waste remains as ash and must be landfilled [6].

It is therefore evident the need to further investigate the question related to the EoL composite treatment scenario and more evident the need for establishing design protocols that positively affect the EoL opportunity of this kind of materials, yet in the first phases of the design process. Reuse is the best option of the European Union's (EU) Waste Framework Directive, second only to reduce. Design strategies must focus on the implementation of re-use of scraps, through the application of design for de/remanufacturing and disassembly rules. This could happen by creating circular supply chains, where scraps become input materials, reducing waste treatment costs and increasing the environmental benefits. The literature however does not provide enough hints and methodologies aimed to make supply chains of composites materials, circular.

The present paper presents a method of analysis in the context of Eco-design whose core is to transform scraps and off-specification products in primary materials for the manufacturing of different goods, also thank to their redesign.

Three are the key strengths of the developed approach: first, it faithfully implements two of the principles of CE, according to which the EoL and the design phases must be strictly bounded, and the circularity concerns a system, not a single organization. Secondly, the method aims to a symbiosis among enterprises that are active on different sectors and several materials; this offers a way out to a critical aspect that in certain sectors endangers CE: the cannibalization and low demand for remanufactured products. Ultimately the method explores innovative employment for composite materials, diminishing their EoL treatment.

Differently from the existing literature, the proposed approach aims to apply the scraps with different functions they were initially conceived for (Sect. 2).

The case study in Sect. 3 implements the proposed methodology and quantitatively evaluates the environmental benefits of the IS of companies that act in different sectors (kitchen equipment/home furnishing and professional appliances): process scraps of the first are analyzed, simultaneously with the product of the second; the re-design enables the use of the scrap to produce coffee grinder components. Results highlight the need for strong cooperation between companies, to take advantage of the products' hidden value. Design strategies to increase the level of applicability of circular strategies, e.g. simplicity in shape and feature of products are key factors for IS. Results are further discussed in Sect. 4, prior to the conclusion (Sect. 5), where future studies are debated; these should focus on the economic impacts, considering not only the technical sphere, but also including the benefits echoing on company's images.

2 Industrial Symbiosis Design Approach

The proposed approach, shown in Fig. 1, aims at supporting enterprises in identifying and evaluating circular strategies for IS with a structured process and enabling them to quantify the environmental benefits of reusing scraps as raw materials. In order to make detached value chains circular and establish a link in their actions, an assessment of the present state (As-is) is needed.

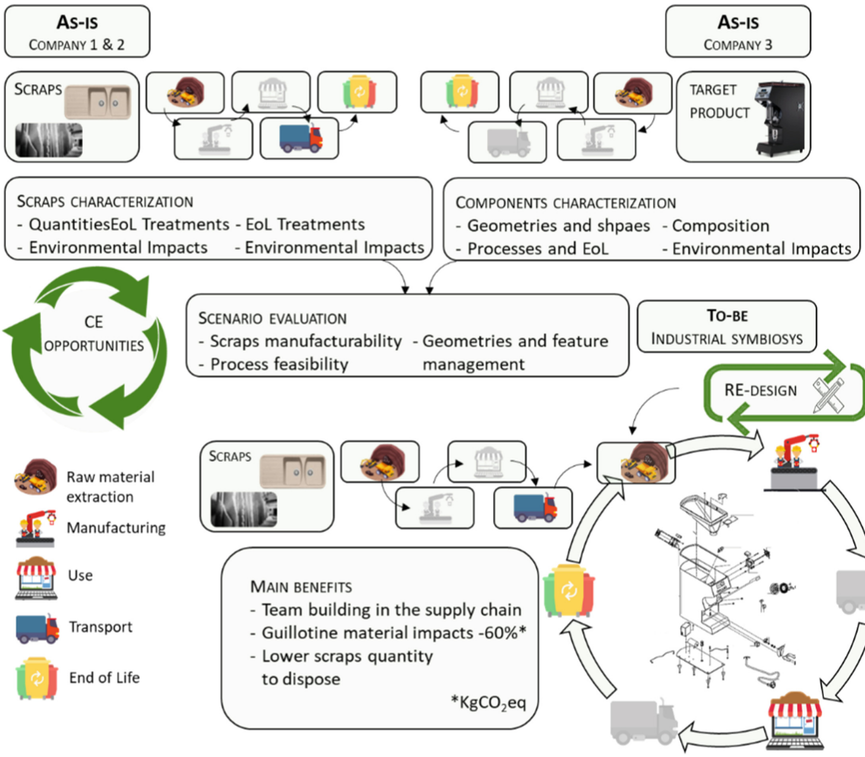

Fig. 1. Scrap characterization phase and potential employment in industrial symbiosis

This consists in a full or partial Life Cycle Assessment (LCA) for one or more product families of the companies. The left side of the graph contains lifecycle stages of enterprises willing to find an innovative use for their scraps, on the right potential user of those. The environmental evaluation allows to have a picture of the current state and identify the most critical phases. However, it is important to rationalize the current process and product status, so it is easier to find the optimal strategies to optimize composite materials waste; this is the scrap characterization phase and consists in:

- Quantifying the scraps produced in a set timeframe (e.g. yearly); this is useful to monitor the amount and the variability level and consequently the availability of a specific scrap on a reference target period;
- Clustering material typology and composition; this is useful to identify potential treatments/machining and performances; in particular:
  - Geometrical properties, surface quality, features and shapes for components, to identify parts with higher/lower level freedom degree (e.g. esthetical vs. functional components); it may be hard to achieve high superficial quality by using scraps and/or by re-manufacturing composite waste;
  - Material properties for components and their technical, mechanical, thermal, and physical performances; i.e. the potential new (composite) materials must be able to withstand to requirements of the components they will be further employed in;
  - Distances (of enterprises of the potential IS and of dismantling centres) and frequencies of disposal;
  - Environmental impacts and criticalities of detached value chains.

This step is important to obtain a clear picture of the potential flow of parts and materials to employ in innovative applications. The second step consists in the component characterization phase. It identifies potential target components to manufacture with alternative materials and processes; this is important because several are the components that must be compliant to multiple constraints that prevent the use of alternative materials of production processes. The potential scenario investigation, i.e. scenario evaluation phase, should focus mostly on linking the material performance (both technical and environmental) and components function with constraints and technical feasibility. In fact, unlikely the components are ready to be made of scraps in their current state of design; nevertheless, small changes open big solutions and make the components compliant to the constraints set by the scraps (i.e. re-manufacturing process cannot employ the same technologies expected to be used in the traditional manufacturing process). The re-design is useful to overcome the challenges projected by the scraps feature and the characteristics to be reached by the target component. A To-Be scenario foresees the identification of one or more circular strategies to apply for the specific situation. By quantifying their environmental impacts/benefits, it is possible to choose the best solution.

By focusing on de/re-manufacturing the method easily finds application for products and scraps made of composite material, whose disposal is very challenging, and recycling is most of the time an unattainable standard. Secondly, it is compliant with the base principles of circular economy. In fact, it strictly links the end of life and first stages of products lifecycles. In addition to that, it expects multiple manufacturers of various sectors to work together to find sustainable solutions and improvements, lower scraps and waste to dismantle. This hides a great strength of the methodology: the symbiosis prevents the risk of cannibalization and low demand for remanufactured products that often distress enterprises and hamper circular initiatives. By identifying an application in a completely different sector, the market of the original product is not endangered neither jeopardized; this must be a great boost for manufacturers to put effort in looking for innovative implementation.

3 Case Study: Include Scraps in Components Manufacturing

3.1 Scraps and Components Characterization

The proposed method was applied by three Italian companies from the Macerata district; their relative distance is not farther than 30 km. Two of them made their scraps available to be worked and employed as secondary raw materials in the production of a professional coffee grinder. The scraps were derived from the manufacturing of marble and porcelain stoneware (Company 1) and sink for domestic kitchens (Company 2). They were both process scraps (i.e. dust or pieces from Computerized Numerical Control - CNC - machining) or pieces discarded because they do not accomplish internal quality standards. Their dimensions are unstable and unpredictable because related to process inaccuracy. The As-Is analysis evaluates the environmental burdens, through LCA methodology and tool, deriving from the extraction, production, and disposal of the annual quantity of scraps produced by Company 1 and 2. Colored icons in Fig. 1 highlight which lifecycle stages were considered.

Table 1 summarizes the Life Cycle Inventory (LCI) data and results for the environmental assessment of the scraps deriving from processes of Company 1 and 2. For each waste type the percentages in weight of annual scraps is indicated, together with the material and respective composition.

Table 1. LCI scraps and Environmental impacts distribution

LC Phase	**Company 1**							
Type	Slime	Pieces						
Quantity*	18%	35%	40% Porcelain stoneware			15%	10% Quartz agglomerate	
Material	Dust-mixed	Marble	Silica sand	Clay	Feldspar	Granite	Quartz dust	Polyester
Composition			6%	48%	46%		93%	7%
Transport	Road, truck							
EoL	Quarry re-development							

LC phase	**Company 2**					
Type	Sink scraps			Sink dust		
Quantity*	87%			13%		
Material	Mineral	PMMA**	Additives	Mineral	PMMA**	Additives
Composition	0,7	0,25	0,05	70%	25%	5%
Transport	Road, truck					
EoL	Pre-treatment (mechanical), Incineration					

Impacts	**<10%**	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-100%

*per year **PMMA= Polymethyl methacrylate

Companies 1 and 2 produce goods made of composite materials; this allows to accomplish the high efficiency of working conditions and durability of products. After being discarded, the scraps of Company 1 are used to fill an old quarry; although smart and sustainable, this solution does not valorize the potentialities of the scraps. Sink scraps are fully incinerated after being pre-treated in dismantling centers. Cells filling quantifies the percentage of environmental burden accounted for each lifecycle phase, for the Global Warming Potential (GWP) indicator. All the analyses were carried out with the support of software SimaPro 8.0, EcoInvent v3.6 database, and results were calculated by the Recipe MidPoint (H) method. The material phase is the most impacting (more than 85%), followed by the EoL phase. Transportation and treatments impacts prior to the final disposal are negligible. Simultaneously, the As-Is analysis requires the environmental assessment of the target product, identified as the one that will host the scraps of Companies 1 and 2 as secondary raw materials. The functional unit for the LCA was the production, use and disposal of a professional coffee grinder. More than 55% in weight it is made of metals and has high recycling rates (up to 70%); the remaining is shredded and sorted as Waste from Electric and Electronic Equipment (WEEE). The coffee grinder is assumed to be used daily for 5 years to produce on average 36 coffees per day, in Italy. Figure 2 shows the results of the analysis of the current scenarios for the coffee grinder for the GWP indicator. Over the whole lifecycle, that counts impacts of about 4,0 E+2 KgCO2eq, the production of the coffee grinder impacts for more than 30%. Regarding the EoL phase, materials recovery, although not at 100%, allows obtaining credits from the EoL treatment.

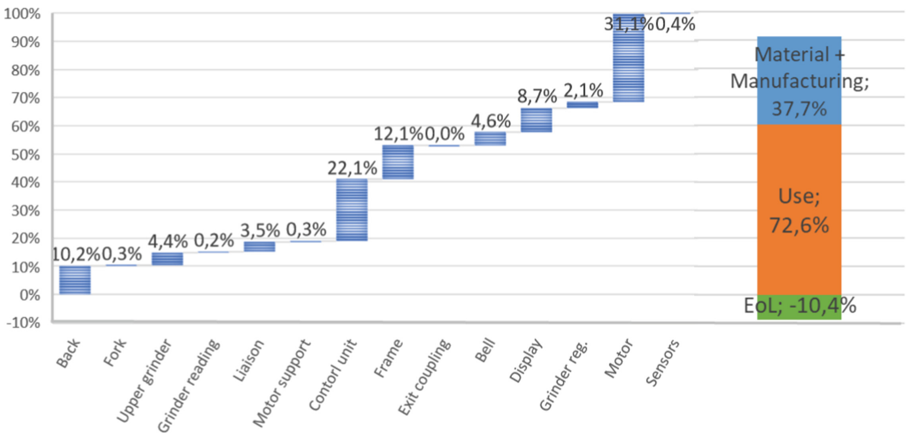

Fig. 2. As-is environmental impacts of professional coffee grinders [KgCO2eq]

The results of environmental analyses, both for scraps and coffee grinder, show several potential improvements; first, avoiding incineration or landfilling of the composite scraps (Table 1) the environmental burden deriving from the actual EoL scenario would be reduced. Secondly, if they were used in the coffee grinder it would lower the material phase impacts.

3.2 Re-design and Innovative Applications

The feasibility of circular scenarios is strictly related both to technological and functional constraints. The scraps of Company 1 and 2 have simple geometries, cannot be heated, extruded neither threaded to be inserted, nor welded, but can be milled. These are strong constraints that must be considered when identifying the potential target component of the grinder. The scraps deriving from sink off-specification have wide flat areas, they have holes (i.e. for water draining) and their thickness is limited to a few millimeters (less than 1 cm). Company 1 provides flat sheets, different in thickness and dimensions (from a few mm to 1 m). According to scraps characteristics, grinder components were classified according to their shape. Three components were identified: the buttons plate, the company logo, and the guillotine kit. The first is a plate in whose holes the buttons fit and thus the grinder is switched to working/off mode; it is also provided with pins and small wings to attach it to the frame; the logo is meant to be attached to the back of the grinder, it is similar to a “v” geometry and presents a simple, curved shape; the function of the guillotine kit is to stop or allow the coffee beans to pass through it when it slides to the right or left respectively. The kit is composed of two screws that link the guillotine and the support used by the barman to activate the blocking system. Its simplicity and small dimensions raise it as the target component.

The main technological complication, both for scraps of Company 2 and Company 1, is the unfeasibility to modify the shape of the scraps, except for cutting/milling processes. Therefore, the buttons plate was discarded among the target components and similarly the logo, because their re-manufacture would require bending the sheet, or the aesthetic constraint would be not accomplished. The guillotine kit was set as the target assembly. It belongs to the bell group and it is located at the bottom of it. The original design expect it made of stainless steel and its production accounts for 3,5% of the environmental burden of the bell group.

The current design of the guillotine (Fig. 3a) expects the part to have a camber (red circle) to allow the component to stop and position in the right place relative to the bell group (light blue part).

A re-design was needed to overcome this obstacle. Starting from the current design, three re-design hypotheses were evaluated: i) modify the bell and add a pin to stop the guillotine; this was discarded because it would make the bell manufacturing process much more complex than the present one (molding); ii) use scraps to obtain the guillotine and the support and link them with a bolt, modify the guillotine and add a second support made of scraps as well, linked by a bolt (Fig. 3b); iii) use scraps to obtain the guillotine and the support and link them with a bolt, add a hole to the guillotine, to insert a bolt (Fig. 3c). The areas with a green profile show how differently the support is linked to the guillotine between As-is and Re-design: the latter requires a bolt instead of a simple screw.

The bolt is necessary because neither the PMMA nor the porcelain stoneware can be threaded. Nevertheless, considering disassembly, the support and the guillotine are easily detachable. In the case of re-using the scraps of company two, the bent part of the sink enables the support to be composed of scraps; instead, this is not possible with the porcelain stoneware or marble, thus the support material is different from the guillotine and is the same of the current (stainless steel), nevertheless disassemblable.

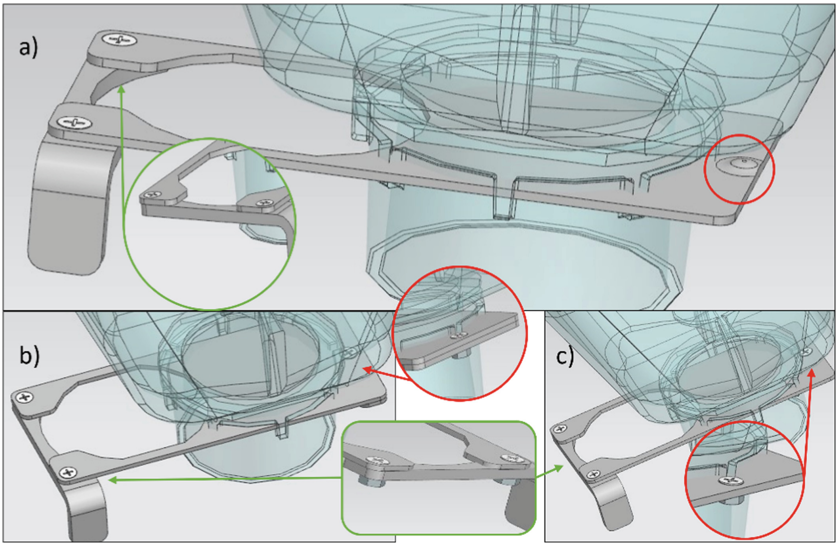

Fig. 3. As-is design (a), first hypothesis re-design (b), definitive re-design (c).

This solution joins the supply chain of coffee grinder Original Equipment Manufacturer (OEM) with those of Company 1 and 2. Scraps now gain new value and life, in a perfect establishment of the CE system. Results show great sustainable potentialities of the implementation of the redesign, as summarized in Table 2.

Table 2. Main design differences and environmental impacts As-is and To-be

	As-is	To-be Company 1	Δ As-is Company 1	To-be - Company 2	Δ As-is Company 2
Design					
Guillotine	Stainless steel	Scraps		Scraps	
Support	Stainless steel	Stainless steel		Scraps	
# Screw	2	0		0	
# Bolt	0	3		3	
Environmental impacts [KgCO_2eq]					
A+M	175,09	174,93	−0,09%	174,85	−0,14%
A+M_KIT	0,2731	0,108	−60,28%	0,03	−88,79%
A+M_Guillotine	0,20	3,23E−02	−83,92%	1,45E−02	−92,80%
A+M_Support	0,069	–	–	8,55E−03	−87,55%

The resources employed in the re-manufacturing process (milling) have been considered and their impacts evaluated through the Recipe MidPoint (H) method in SimaPro 8.0, EcoInvent v3.6 database.

Once identify the re-manufacturing process, according to the proposed method, the environmental evaluation of the new scenario allowed to assess whether those re-manufacturing activities let the companies achieve lower environmental burdens. There are benefits from the environmental point of view in introducing the sink and porcelain stoneware scraps as secondary raw material in the coffee grinder.

The changes in materials (from low alloyed steel) to plastic composites (Mineral + PMMA + Additives) and the re-design lead to a reduction of more than −90% of overall impacts related to the production of the guillotine and −88% of the whole kit. Although lower, also the introduction of the scraps of Company 1 ensures lower environmental impacts related to the production of the guillotine (−83%) and the full kit (−60%). The results also include the transport of the scraps from one manufacturing site to the next. The additional environmental savings are due to the avoided impacts related to the scrap disposal (about 5E−3 kgCO2eq for Company 2 and 1,85E−3 KgCO2eq for Company1).

4 Discussion

The present section will discuss the main outcomes and criticalities arisen from the implementation of the proposed method. The obtained results show great potentialities and benefits deriving from the use of scraps for producing the guillotine kit. Since sink scraps of Company 2 are used both for the guillotine and the support, they bring to higher environmental impacts savings than the case of reuse scraps of Company 1, in which the guillotine support is made of stainless steel. The benefits mainly stand into:

- avoided impacts related to the extraction of the raw material (the new material already exists, and any other resources must be extracted from geosphere);
- avoided impacts related to the EoL treatment and disposal of the scraps; becoming secondary raw material, they do not undergo any EoL processing (i.e. shredding, landfilling, incineration, etc.).

The novelty of the proposed methodology is its purpose to find innovative applications and employment of scraps to existing or new products, instead of reintroducing them in the same loop they were firstly used:

- If Company 1 and 2 are willing to use their scraps to produce new products, they would not be able to re-use them as they are, instead an additional treatment (when possible) should be carried out. In rare cases when it is possible, these are expensive, energy-demanding processes.
- Despite the costs of material recovery, when they are recycled, composite materials can restore their performances [7]; if they do not, the OEM must either reject the recycled material or use it to produce a product with lower performances (risk of image jeopardization or cannibalization).

The methodology enables the valorization of certain materials (such as composite materials) whose management at the EoL is, currently, extremely inefficient, and unsustainable. Nevertheless, some criticalities were encountered and from them authors derived guidelines and design strategies that support a successful establishment of IS.

- *Dismantler's involvement;* Enterprises have very low awareness of how scraps and waste are treated; the analysis of the EoL of the scraps encountered difficulties in tracking all the steps, especially for Company 2. First it was based upon the information provided by the OEM; this was poor and generic and according to it, waste was landfilled. The dismantler was then interviewed to gain more details and the researchers were directed to a second dismantler and found out that the final confinement of the waste was the incineration. This was proof that manufacturers often do not hold detailed information about EoL which happens out of their gates.
- *Networking;* strictly related to what previously explained, there is a need for cooperation both with downstream and upstream suppliers. Enterprises should be open-minded and establish new partnerships. Those established with suppliers of the product value chain must aim to provide information about the product, those settled with businesses from different markets pave the way to countless innovative solutions that prevent materials to be disposed after the first use, or before (in the case of process scraps).
- *Simply shapes;* withstanding the functional, technical, aesthetic constraints set multiple boundaries; a simple design helps in this sense and paves the way to the feasibility of the restricted number of processes that can be applied to the waste materials and consequently to the components. For example, plastic composite material can either be welded nor extruded, otherwise they lose the appropriate conditions and characteristics. The design (or re-design) phase must keep in mind this point.
- *Modularity*; the reuse of scraps requires often design modification on components. A modular structure for products minimizes the changes on components (mostly functional modules, rather than aesthetic), thus reducing the time and cost of modifications, while increasing the design flexibility. A modular design of target products may lower components characterization phase time and enable application to multiple models of the same scrap typology. A modular product leads to more standardized parts and production processes; in the case of IS, this means also a more standardized re-use and/or re—manufacturing process. Multiple are the benefits; among them the most important are the reduced analysis time and increased volume of scraps destined to the circular loop.
- *Disassembly;* scraps reused from business different from traditional suppliers may lead to the introduction of additional material types. This goes against the general disassembly guidelines, according to which the number of employed materials should be minimized. In order to maximize environmental benefits linked to the reused of composites material and not hamper the target product recyclability (coffee grinder in this case), the re-design must make proper considerations about disassemblability.
- *Distances;* the case study involved companies settled in the same district. Proximity is very useful to maintain strong relationships and lower the environmental burden due to the transport phase.

5 Conclusion

The unique solution to sustainably use and manage natural resources is the paradigm of CE. This requires enterprises to think of themselves as part of a system, rather than a self-standing organization and thus give birth to cooperation and symbiosis with other enterprises, also those main activities do not involve the same sectors.

This is perceived as a drastic transformation that overruns the daily activities and reaches the vision and mindset of the OEM. Therefore, the metamorphosis must be planned, assessed, and supported by proper products and processes design.

The EU boosts this change and guides for businesses (i.e. waste framework), but the literature presents wide gaps in investigating methods and approaches to support the establishment of IS. Moreover, the higher performances required to material have been triggered the production of innovative materials, able to combine complementary characteristics. Unfortunately, it is extremely hard to valorize those materials once they are discarded by industrial processes or the products where they are employed to reach their EoL. It is therefore urgent to further investigate the question related to the EoL composite treatment scenario by establishing design protocols that positively affect the EoL opportunity of this kind of materials, yet in the first phases of the design process.

In this context the present work proposes a method in the context of eco-design that guides in the choice of which and how scraps can be reused and gain new value, after being discarded. The core of the method is the redesign of components of certain goods, so that their material can be substituted with scraps deriving from the value chain of other composite products. The results show positive environmental effects of the redesign implementation. However the application of the methodology outlines important factors to consider while finding possible paths to establish successful IS: dismantler's involvement, networking, simple shapes, modularity, disassembly, distance.

Future works will focus on economic evaluation of the proposed de-manufacturing actions that have been explored from the technical and environmental points of view, and the identification of design strategies for all the companies to facilitate or support CE strategies implementation.

Acknowledgement. The activities are related to the project MARLIC "Marche Applied Research Laboratory for Innovative Composites", which is part of the project POR Marche Region FESR 2014–2020, Asse 1 – OS 2 – Intervento 2.1.1 e Asse 8 - OS20 – Azione 20.1 – Intervento 20.1.1.

References

1. Demartini, F., Tonelli, F., Govindan, K.: An investigation into modelling approaches for industrial symbiosis: a literature review and research agenda. Clean. Logist. Supply Chain **3** (2022). https://doi.org/10.1016/j.clscn.2021.100020
2. Remery, M., Mascle, C., Agard, B.: A new method for evaluating the best product end-of-life strategy during the early design phase. J. Eng. Des. **23**(6), 419–441 (2012). https://doi.org/10.1080/09544828.2011.605061
3. Job, S., Leeke, G., Mativenga, P.T., Oniveux, G., Pickering, S., Shuaib, N.A.: Composites Recycling. Where are we now? Composites UK Report (2016)

4. Mativenga, P.T., Sultana, A.A.M., Agwa-Ejonb, J., Mbohwab, C.: Composites in a circular economy: a study of United Kingdom and South Africa. Procedia CIRP **61**, 691–696 (2017). https://doi.org/10.1016/j.procir.2016.11.270
5. Oliveux, G., Bailleul, J.-L., Salle, E.L.G.L.: Chemical recycling of glass fibre reinforced composites using subcritical water. Compos. A Appl. Sci. Manuf. **43**, 1809–1818 (2012). https://doi.org/10.1016/j.compositesa.2012.06.008
6. Jacob, A.: Composites can be recycled. Reinf. Plast. **55**, 45–46 (2012). https://doi.org/10.1016/S0034-3617(11)70079-0
7. Khalid, M.Y., Arif, Z.U., Ahmed, W., Arshad, H.: Recent trends in recycling and reusing techniques of different plastic polymers and their composite materials. Sustain. Mater. Technol. **31** (2022) https://doi.org/10.1016/j.susmat.2021.e00382